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《Technical Note》

Reference Spent Fuel and Its Characteristics for a Deep Geological Repository Concept Development

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Abstract

This study addresses the reference spent fuel and its characteristics for developing a geological repository concept. As a disposal capacity of the reference repository system to be developed, spent fuel inventories were projected based on the basis of the Nuclear Energy Plan of the Long-term National Power Program. The reference spent fuel encompassing a variability in characteristics of all existing and future spent fuels of interest was defined. Key parameters in the reference fuel screening processes were the nuclear and mechanical design parameters and the burnup histories for existing spent fuels as of 1996 and for future spent fuels with the more extended burnup the initial enrichment and its expected burnup. The selected reference fuel was characterized in terms of initial enrichment, burnup, dimension, gross weight and age. Also the isotopic composition and the radiological properties are quantitatively identified. This information provided in this study could be used as input for repository system development and performance assessment and applied in fuel material balance evaluation for the various types of back-end fuel cycle studies.

Key Words : reference spent fuel, characterictics, disposal

1. Introduction

A primary function of the waste repository is to isolate radioactive waste from the accessible environment for a sufficiently long time. Its performance assessment is to simulate and to verify performance or expectation that the repository can isolate radioactive materials within standards specified in regulations for public health and safety as expected.

Although a radioactive waste disposal system is not so complicated as a nuclear power plant, its total system performance and long-term safety assessment include inevitable uncertainties due to the limited information and data of geo-environment and ecosystem that may be altered for a long time. In the case of a high-level waste (HLW, inclusive of spent fuel), especially, additional information has to be considered to analyze how much high radiation and decay heat

from HLW would affect the geo-environment surrounding the repository, which may cause another uncertainties.

Some of uncertainties in safety or performance assessment may be reduced by a repository system well defined with reasonable propriety of engineering aspects. In order to develop a reference geological repository system with technical feasibility, reasonable cost and long-term safety and to collect sufficient engineering data for further system study and optimization, system design at pre-conceptual level is necessary at minimum. For such design, it is prerequisite to determine the reference spent fuel that bounds the effected range of representative characteristics and volumes of all spent fuels from the existing and planned nuclear units.

At present, eleven PWR units and three CANDU units are in operation and another 6 units under construction. According to the Nuclear Energy Plan of the Long-term National Power Program announced in 1995, seven units would be added to by the year 2010. In this study, total quantities of spent fuels generated from the existing nuclear power plants and those planned by the year 2010 were estimated as the disposal capacity of a reference repository system. The reference spent fuel encompassing a variability in characteristics of all existing and future spent fuels of interest was defined based on the nuclear and mechanical design parameters and the burnup histories for existing spent fuels as of 1996 and for future spent fuels with the more extended burnup the initial enrichment and its expected burnup. The selected reference fuel was characterized in terms of initial enrichment, burnup, dimension, gross weight and age. In addition, radiactivity, decay heat and radiation spectrum in the reference spent fuel were quantitatively analyzed and summarized. Especially, major radionuclides that would control

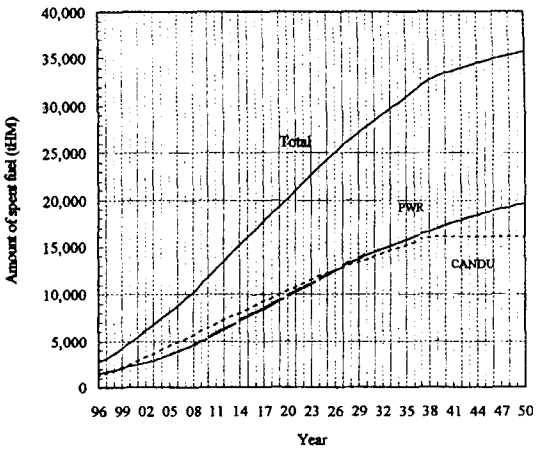

Fig. 1. Spent Fuel Arising from the Exiting Reactors and the Planned by 2010 During 40 Years-lifetime, Except for Kori#1(30 Years-lifetime)

the long-term safety of the geological repository were selected in comparison with the ingestion hazard index of natural uranium ore. This information provided in this study could be used as input for repository system development and performance assessment and applied in fuel material balance evaluation for the various types of back-end fuel cycle studies.

2. Spent Fuel Arising

As a disposal capacity of the reference repository system, the total spent fuel inventories to be disposed of were estimated based on spent fuels storing at the reactor sites as of 1996 and for the further projection the expected spent fuel discharge rate of the existing and planned reactors during their lifetimes. It was assumed that the lifetime of all reactors is 40 years and for Kori-1 30 years. Annual discharge rate of spent fuel from the advanced PWR to be introduced after the year 2007 was estimated to be approximately 22.3MtU (tons of uranium) as follows:

[(1,300MWe)(0.8/0.31) × 1/55,000MtU/MWd] × 365 days/year = 22.3MtU/year, in which the reactor efficiency was assumed to be 31%, the electrical generation capacity 1,300MWe, the overall capacity factor 0.8, and the average discharge burnup of fuel 55,000MWd/MtU.

Total amount of spent PWR and CANDU fuels from all reactors consisting of 24 PWR reactors and 4 CANDU reactors were estimated to be approximately 36,000tHM as shown in Fig.1, in which Kori #1 was assumed to be closed in the year 2008. Of the projected spent fuel inventories, PWR fuels comprise ~20,000tHM (55%) and CANDU fuels ~16,000tHM (45%). These volumes are equivalent to about 45,500 PWR fuel assemblies based at 0.44 MtU/assembly and about 842,000 CANDU fuel bundles based at 0.019 MtU/bundle, respectively.

3. Properties of the Spent Fuel

In general, spent fuels are identified and characterized with respect to the design and operating properties of reactors. In the case of PWR, in particular, various types of fuels with different design specifications are using as given in Table 1. Besides the radiological properties of the spent fuels are depending on the operating conditions of the reactors or the fuel burnup histories. Of course, the decay characteristics of radionuclides contained in spent fuels depend upon the decay time after discharge from the reactor. Consequently, that spent fuels with a number of different properties (geometry, dimension, weight, cooling time, burnup, radiological concentration, decay heat, etc.) are generated.

In this section, the mechanical and nuclear design parameters and burnup characteristics of the spent fuels were investigated as a preceding process for determining the reference spent fuel whose bounding characteristics could be representative of all spent fuels of interest.

3.1. Aspects of the Fuel Design

A PWR fuel rod consists of several hundred UO2 pellets stacked under helium pressure in a zircaloy tube. These fuel rods are assembled into a PWR fuel assembly, of which fuel rod arrays being used in Korea are typically 14 × 14, 16 x16 and 17 × 17. An enrichment of typical PWR fuel has ranged 3.5 to 4.2% of U-235 and it has recently tended to increase up to 4.5%[3]. As listed in Table 1, dimensions of PWR fuel assemblies are slightly different from one another with respect to the configuration of fuel rods. The dimensions of 14x14- and 16x16-fuel assemblies are 19.8cm × 19.8cm in cross-section and 405.8cm in length and those for 17x17-fuel assembly are 21.4cm × 21.4cm in cross-section and 405.8cm in length. For Korea Standard Fuel Assembly (KSFA) with 16x16 fuel rods array, however, the dimensions are 20.7cm × 20.7cm in cross-section and 452.8cm in length. One of the special features, from the aspects of spent fuel handling for packaging or encapsulation, is that the height of KSFA is greater by about 47cm. Overall weight of the fuel assembly also depends on the nuclear and mechanical design specifications, but it generally ranges from approximately 515kg to 665kg inclusive of the weight of uranium.

For CANDU reactor, natural uranium with 0.71% of U-235 is used as the fuel material. A CANDU fuel bundle consists of 37 fuel rods in cylindrical arrangement with 10.2cm in diameter and 49.5cm in length. The bundle weight is about 23.6kg including the uranium of 19kg to 20kg.

Fig. 2 shows the accumulated amount of spent fuels annually generated from the reactors from

Table 1. General Parameters of Nuclear Fuel used in Korea Nuclear Power Plants

Item		K1			K2		K3&4			YG1&2		UC1&2		YG3&4/UC3	WS1&2&3
Reactor Type		PWR			PWR		PWR			PWR		PWR		PWR	CANDU
Reactor Power(MWe)		587			650		950			950		950		1000	679
Fuel Rod Arrary		14×14			16×16		17×17			17×17		17×17		16×16	1/6/12/18
FUEL ASSEMBLY	Supplier	WH		KOFA	WH	KOFA	WH		KOFA	WH	KOFA	PRAMA	KOFA	ABB/CE Sys.-80	KAERI
		STD	OFA	KWU	STD	KWU	STD	OFA	KWU	OFA	KWU	STD	KWU	KFSA	CANDU
	Rod/Assembly	179		179	235	235	264		264	264	264	264	264	236	37
	Assembly/Core	121		121	121	121	157		157	157	157	157	157	177	380×12
	Length(cm)	405.66		405.8	405.8	405.8	405.8		405.8	405.8	405.8	405.8	405.8	452.8	49.53
	Fuel Length(cm)	365.8		365.8	365.8	365.8	365.8		365.8	365.8	365.8	365.8	365.8	409.4	38.90
	Cross-section(cm^2)	19.27^2		19.27^2	19.27^2	19.27^2	21.4^2		21.4^2	21.4^2	21.4^2	21.4^2	21.4^2	20.7^2	ϕ 10.25
	OD of Rod(mm)	10.07	10.2	10.75	9.5	9.5	9.5	9.14	9.5	9.14	9.5	9.5	9.5	9.91	13.1
	Clad Thick.(mm)	0.62	0.62	0.65	0.57	0.57	0.57	0.57	0.64	0.57	0.64	0.57	0.64	0.635	0.4
	Total Wt.(kg)	578	515	570.83	594	584.2	665	616	659.7	616	659.7	665	659.7	653.6	23.6
	Uranium Wt.(kg)	400	367	382	410	392	461	424	440	424	440	461	440	428	19.1
	Zircaloy Wt.(kg)	91.4	99.7	120.2	98.57	119	110	117	140	117	140	110.5	140	135	4.5-
	Inconel Wt.(kg)	3.29	1.76	2.59	4.98	5.58	4.3	0.6	3.56	0.6	3.56	5.15	3.56		-
	SUS304 Wt.(kg)	3.28	18.2	15.08	0.62	15.77	2.9	0.2	17.45	0.2	17.45	4.23	17.45		-
	Enrichment (w/o)	2.1-3.2			1.6-3.6		1.6-3.8			1.6-3.8		1.6-3.8		1.28 -3.34	Natural Uranium

• K, YG, UC and WS mean Nuclear Power Plants at Kori, Younggwang, Ulchin and Wolsung site.

Table 2. Spent PWR Fuel Projection with Respect to the Expected Average Burnup

Period	Average Burnup (MWd/tHM)	Spent PWR Fuels to be disposed of	
		Quantity (tHM)	Fraction (%)
~ 1989	30,000 ~ 33,000	500	3
1990 ~ 1996	33,000 ~ 39,000	1,000	5
1997 ~ 2008	~ 45,000	3,000	15
after 2009	~ 45,000	8,100	41
	≥ ~55,000	7,400	36
Total		20,000	100

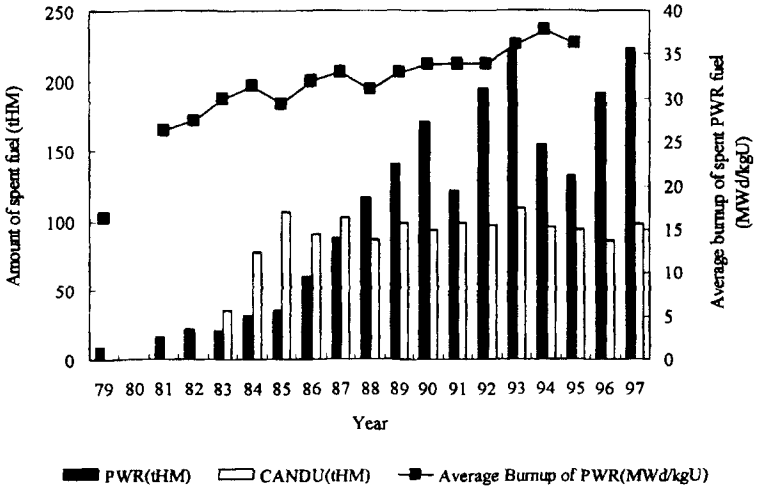

Fig. 2. Spent Fuel Inventories Annually Generated from the Reactors and the Trend of the Average Burnup

the year 1979 to 1997. By the end of 1997, total amount of spent PWR fuels is 4,434 assemblies equivalent to about 1,950tHM. The corresponding amount of CANDU fuels is about 1,371 tHM. From the aspect of PWR fuel geometry and type, the 17x17-fuel assembly reaches about 66% of total amount of spent PWR fuels. Especially, the fraction of spent 17x17-KOFA that has been used in most PWRs, except for Kori Unit 1&2, has increased up to 30% since the year 1990. Because spent 16x16-KSFAs with greater height by about 50cm have just started to be generated from the Younggwang Unit 3&4 since 1996, their inventories are not recognized at present. However, its amount is expected to increase remarkably in early 2000s due to Ulchin Unit 3&4, Younggwang Unit 5&6 and Ulchin Unit 5&6. Nevertheless, the fraction of spent 17 x 17-KOFA fuels would be the greatest of the total spent fuel inventories by around 2007.

3.2. Aspects of the Spent Fuel Burnup

Foreign countries with advanced nuclear

technology are focusing on the development of extended or high burnup fuel for the higher uranium utilization and the lower nuclear energy generation cost. Practically, the burnup level of spent PWR fuel has already reached or over 50,000MWd/tHM in some commercial reactors. According to the development programs of high burnup fuel that has being carried out in the US, Germany and Japan, the nuclear fuel designed with average burnup of 50,000 to 60,000MWd /tHM is expected to be developed before this century [4].

In Korea, the fuel burnup has been gradually extended through the increase in enrichment and the longer irradiation time in-core. By the middle of the eighties, average burnup level of most spent PWR fuels was about 33,000MWd /tHM for a 12 months-fuel cycle. From the late eighties, it has reached about 39,000MWd /tHM by increase in the fuel enrichment from 3.2% to about 3.8% (which has resulted in increase in the irradiation time of fuel in core from 12 months to 15 -18 months). In the case of VANTAGE5H with enrichments of 4.0% to 4.5%, which has been recently used in PWR, the average burnup is reaching about 45,000MWd /tHM and sometimes over 52,000MWd/tHM[3]. The recent trend of average burnup level of spent PWR fuels discharged from PWRs as of 1996 is shown in Fig. 2, in which 96 spent fuel assemblies generated from Younggwang 3&4 in 1996 are not considered because of the limit of the information available. As shown in the figure, average burnup of spent PWR fuel has increased year by year and reaches about 40,000MWd /tHM in recent years. Considering such trend of fuel burnup toward increase, it is expected that average burnup level of the spent fuel from APWR after the year 2007 would reach about 55,000 to 60,000 MWd/tHM [2].

4. Determination of the Reference Spent Fuel

This section represents general considerations and principles to define the reference spent fuel to be disposed of. As discussed previously, two kinds of fuel, PWR- and CANDU-fuel, are basically generated in Korea and the nuclear and mechanical properties of the fuels are slightly different from one another with respect to the fuel designer or supplier, except for the CANDU fuel. Considering that there are inevitably such a broad variation of spent fuel properties to be accommodated by the reference repository system to be developed, the reference fuel must be representative of the reasonably conservative average fuel from the aspects of the nuclear design and the mechanical as "an imaginary fuel".

4.1. General Considerations and Screening Processes

Initial enrichment of the reference spent fuel is one of the key parameters affecting the radiological source-term evaluation for the performance and long-term safety assessment of the geological repository system, because, as mentioned previously, it would be very closely related with the higher burnup of the nuclear fuel. In this study, the expected burnup level of the reference spent fuel was determined first through analyzing the available burnup information of the spent fuels of interest. Then the available initial enrichment range was estimated from the relationship between the spent fuel burnup and the enrichment that was resulted from the Characteristic Data Base (CDB) Program [5]. This program was performed by the Oak Ridge National Laboratory to provide a database of the characteristic information of most spent fuels

generated from the commercial nuclear reactors in the U.S. for Office of Civilian Radioactive Waste Management. The results of this program shows the projected enrichment-burnup distribution of spent PWR fuel, in which the burnup levels of 40,000MWd/tHM and 45,000MWd/tHM are compatible for enrichments of 3.0 to 4.42% and 3.5 to 4.96%, respectively. Such relationship between the spent fuel burnup and the fuel enrichment would encompass the Korean cases.

In order to investigate the burnup trend of the spent fuels from the existing and the planned reactors, total spent PWR fuels projections of interest (20,000tHM) are quantified with respected to several groups of the average fuel burnup, as given in Table 2. Comparing with the total amount of spent PWR fuels, the portion of the fuel quantities generated by the end of 1996 are only about 8% and the spent fuels with burnup (45,000MWd/tHM are about 64%. The value of 45,000MWd/tHM in the table is an assumed one regarding the current increasing trend in fuel burnup. Besides, the burnup levels of spent fuels to be generated from the APWRs after the year 2007 are assumed to be 55,000MWd /tHM. From such analyses of the tabulated data, the fuel burn of 45,000MWd/tHM was determined as the nominal burnup of the reference spent PWR fuel and 55,000MWd/tHM as an alternative for the potential for more extended burnup of the future spent fuels. An initial enrichment of the reference spent PWR fuel was estimated to be about 4.0% for 45,000MWd/tHM and 4.5% for 55,000MWd /tHM based on the results of the US' s CDB program.

The reference burnup of the spent CANDU fuel was determined to be 7,500MWd/tHM because only natural uranium with fissile content of 0.71% has been typically used as the fuel material and the burnup history of the fuel in core was not so complicated.

A cooling time of the reference spent fuel after discharge from the reactor is also important parameter in developing the concept of the reference repository system, because the radionuclide inventory and the decay heat rate of the spent fuel are reduced exponentially as a function of the time. Of course, the longer cooling time of the spent fuel may provide the more positive effects on the repository system from the viewpoint of the economics and the safety. Considering the limited lifetime (30 to 50years) and the economics of the interim storage facilities prior to the disposal phase, however, the cooling time of the spent fuel to be disposed of should be optimized from the various aspects such as the economics, safety, and any national strategy of spent fuel management. In this study, the 40 years was taken as the nominal cooling time of the reference spent fuel. The longer cooling periods (50 to 100 years) remain as the alternatives for the trade-off study on the optimization of the repository system to be performed in the future.

The mechanical properties of the reference fuel such as geometry, dimensions and weight are essential parameters affecting the design of the disposal canister and near-field of the repository system as well as the handling processes for the waste encapsulation and emplacement. In defining such properties of the reference fuel, therefore the conservative values should be taken from the design information of all types of fuels to be expected in Korea. As listed in Table 1, the mechanical design characteristics of CANDU fuels are the same while the dimensions of PWR fuels are slightly different from one another with respect to the configuration of fuel rods. As discussed in the previous section, the greatest cross-sectional dimensions are 21.4cm×21.4cm

Table 3. Input Parameters for ORIGEN2 Calculations

Parameter	PWR		CANDU
	Nominal		alternative
Enrichment (wt.% of U-235)	4.0	4.5	natural uranium
Average Burnup (MWd/tHM)	45,000	55,000	7,500
Specific Power (MW/tHM)	37.5		25.5
Effective Full Power Day per Cycle	400	488	294
Others	*		*

* Total irradiation time of the PWR fuel is assumed to be 400 days with two times of refueling periods (106 days per each) while CANDU fuel is on-power refuelling.

for the 17 × 17 fuel assembly (KOFA), while the greatest length is 452.8cm for the 16x16-KSFA. Of the overall weights of the fuel assembly ranging from approximately 515kg to 665kg inclusive of the weight of uranium, 665 kg was taken as the total gross weight of the reference fuel.

4.2. Reference Spent Fuel

The reference PWR and CANDU fuels that were determined through qualitative analyses as mentioned above are:

- types of the reference spent fuel
  - spent PWR fuel assembly
    - fuel rod array : 17 × 17
    - total weight : 665 kg
    - dimensions : 21.42 cm^2 (cross-section) × 453cm (length)
  - spent CANDU fuel bundle
    - fuel rod array : 37 rods in bundle
    - total weight : 25 kg
    - dimensions : 10 cm (diameter) × 49.5 cm (length)
- initial enrichment and discharge burnup of the reference fuel
  - spent PWR fuel assembly
    - nominal burnup case : 4.0wt.% for 45,000MWd/ tHM
    - high burnup case : 4.5wt.% for 55,000MWD
  - spent CANDU fuel bundle
    - 0.71 wt.% (natural uranium) for 7,500 MWd/tHM
- cooling time before disposal : 40years
- disposal capacity : 36,000 ton of heavy metal (tHM)
  - spent PWR fuel : 20,000 tHM (45,500 Assemblies)
  - spent CANDU fuel : 16,000 tHM (842,100 Bundles)

Considering that a HLW disposal technology development program would be lasted for 20 to 30 years, such bounding reference fuel characterization values should be continuously revised further with respect to the properties of future fuel and the long-term national nuclear energy program.

5. Characteristics of the Reference Spent Fuel

A nuclear fuel assembly (or bundle) consists of uranium fuels and metal components of cladding and other structural parts. As the nuclear fuel is irradiated in the reactor, radioactive materials such as fission and activation products and actinides are created in the fuel. Fission products are the new materials that are created when heavy elements (uranium and plutonium) are split

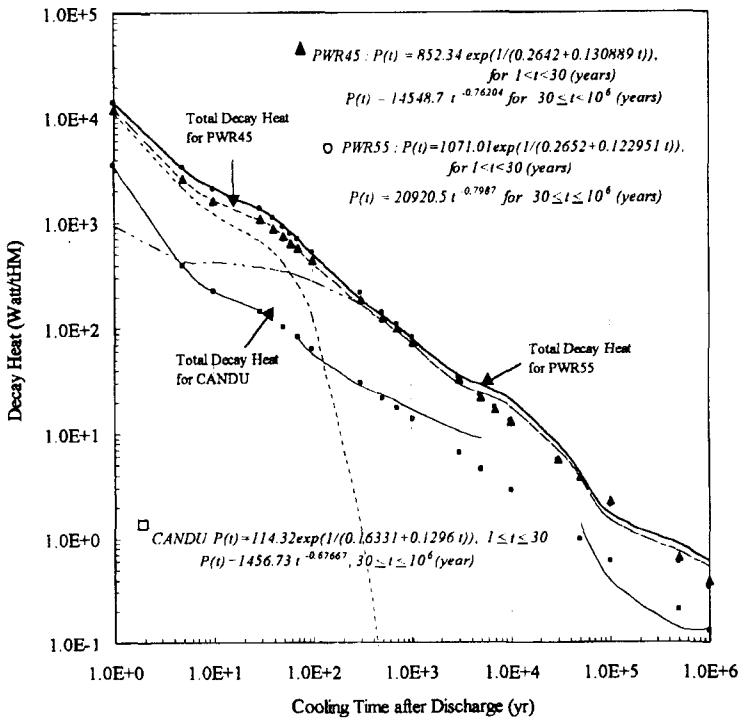

Fig. 3. Decay Heat of Spent PWR and CANDU Fuels and the Approximation Formula for Decay Heat Extimation

in the fission process. Important fission products are iodine (I-129, I-131), cesium (Cs-134, Cs-135, Cs137) and strontium (Sr-90). Activation products are created when impurities in fuel material and fuel structural materials absorb neutrons that are formed in the fission process. Actinides include the uranium and the heavier elements (transuranics) that are formed when uranium absorbs neutron(s) without fission, in which the decay products of uranium and transuranics are also included. Such actinides decay in a series of steps in decay chains, in which some radionuclide contents decrease with time like fission and activation products but others increase(ingrowth). Therefore, most fission and activation products (short- and medium-lived elements) decay out to the negligible extent for several hundred years after discharge but long-lived actinides still maintain the radioactivity and generate the decay heat for a long time. This causes some issues in designing the spent fuel repository system and assessing the long-term performance and safety with high credibility. For the concept development of the reference repository system, it is important to know the magnitude of radionuclide content (gram concentration or radioactivity), decay heat, radiation intensity in the reference fuel and to identify the major radionuclides affecting in the long-term performance of repository system.

In order to provide such information, in this study, the radionuclide inventories in the reference spent fuel were analyzed quantitatively in terms of activity (Ci/tHM), residual decay heat (Watt/tHM), hazard index of important nuclides (volume of water/tHM) and the radiation

intensity. Such data for spent PWR fuel with 45,000MWd/tHM and spent CANDU fuel with 7,500 MWd/tHM were calculated by means of ORIGEN2 code. The specific input parameters for the calculations are listed in Table 3. Specific power (or power density) during the reactor operation was assumed to be 37.5 MWd/tHM for PWR and 25.5 MWd/tHM for CANDU.

5.1. Decay Heat

The decay heat is a thermal energy resulting from the radioactive decay of the radioactive materials in the spent fuel after the discharge from the reactor. Many of the technical uncertainties associated with the underground repository system are related to the decay heat from the waste. Such thermal energy will eventually transport from the waste package to the ground surface through the waste package emplacement area, and the surrounding and overlying rock. Thus migration of thermal energy will impact on the integrity of the engineered barrier components (disposal container, the buffer and/or backfill materials, the sealing materials, etc.) and the host rock and surrounding rock, the stability of the underground facilities, the overlying aquifers or groundwater flows, and the biosphere. To assure that the thermal energy released from the waste will not have a detrimental effect on the repository system, therefore, a systematic design of the repository satisfying the limits associated with thermal and thermomechanical stability under the disposal conditions has to be developed. Such limits can be specified in terms of temperatures, thermomechanical and thermohydrological criteria with regard to the specified site.

This section represents the magnitude of the decay heat in the spent fuel to be disposed of in the repository system, which will be used as

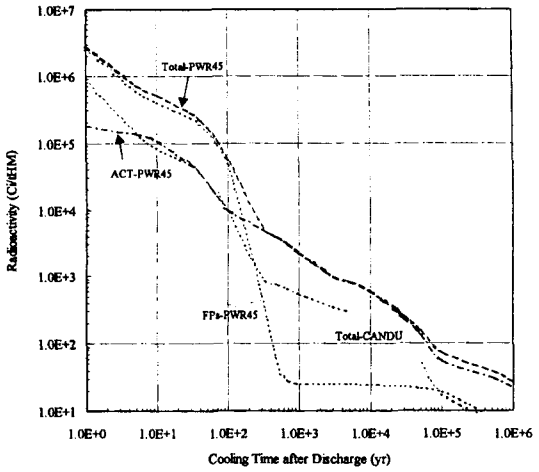

Fig. 4. Radioactivity in Spent PWR Fuel Irradiated with 45, 55 GWd/tHM(PWR55) and Spent CANDU Fuel

thermal source term for the thermal and thermomechanical stability analysis. The major elements contributing to the total decay heat and their long-term behaviors with regarding the time are also analysed.

Fig.3 shows the residual decay heat in the reference PWR and CANDU fuels (spent PWR fuels with 45,000 and 55,000MWd/tHM: herein after PWR45 and PWR55, respectively; spent CANDU fuel with 7,500MWd/tHM: herein after CANDU7.5) at different decay times up to one to million years after discharge. As shown in the figure, fission products (mainly Sr-90 and Cs-137) dominates total decay heat of the spent fuel in early stage of cooling time and its contribution to total heat power reduces as time increases. At around 60 years after the discharge, the decay heat of the fission products is almost the same with that of the actinide elements and then continue to drop rapidly around 70 to 100 years after the discharge. While heavier nuclides (mainly Pu-238, Am-241, Cm-244) begin to predominate after just over one hundred years and after around 300 years mainly determine total decay heat of

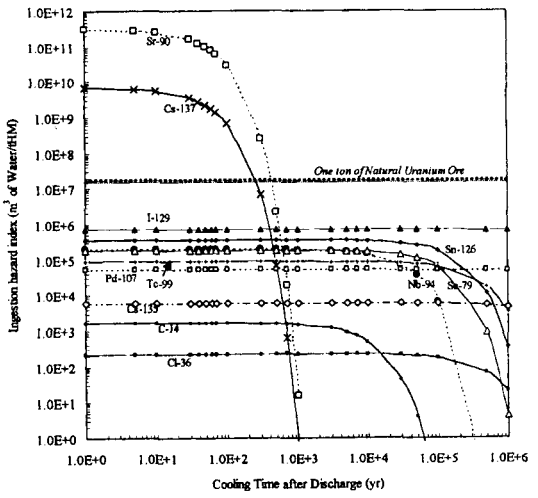

Fig. 5. Radioactive Ingestion Hazard Index of Fission Products and Activation Products Containing in PWR45

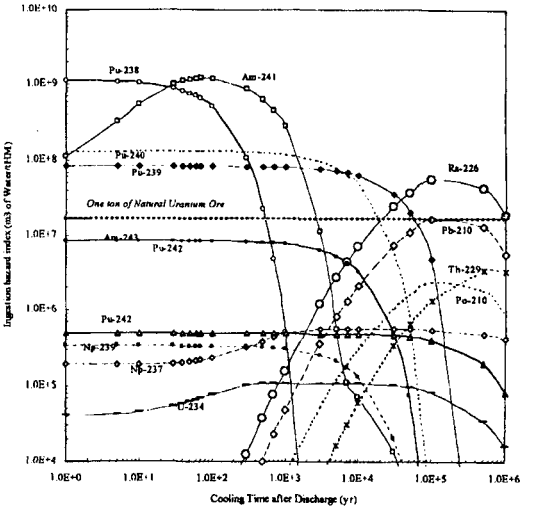

Fig. 6. Ingestion Hazard Index of Actinides Contained in Spent PWR Fuel Irradiated with 45 GWd/tHM(PWR45)

the spent fuel. In the figure, also, simple approximation formulas to estimate total decay heat in the spent fuel with respect to decay time are given. For example, the approximation values for PWR45 are demonstrated as white circles and filled triangles on the solid or dot line, the results of ORIGEN2 calculation. Such comparisons of the approximated values and the calculated show that the approximation formulas give generally good estimations within 1,000 years after the discharge, so that they could be used as the heat-source parameter even in the transient thermal analyses of a geologic repository system.

5.2. Radioactivity and Major Radionuclides

The radionuclide content of the spent fuel is mainly depending on the reactor operating conditions and the burnup history of the fuel while the fuel is irradiating in the core. In general, the fuel burnup, as a total energy extracted from a unit mass of the fuel, is particularly important for the long-lived nuclides inventories. While the relatively short-lived nuclides are controlled by specific power, i.e. the energy extracted every second from a unit mass of the fuel because they are short-lived in comparison with the fuel irradiation time.

Fig.4 shows that the total radioactivities in PWR45 and CANDU7.5 reduce with time after discharge with logarithmic scales to allow longer time span from one year to 106 years. This figure also shows how much fission products and actinides contribute to the total activity in the spent fuel during the given time span. The activity is dominated by fission products for the initial 100years, while after 500years actinides dominate. In the long perspective, as radioactive materials in the spent fuel decay the spent fuel will come to resemble the mineral that was originally mined to produce the nuclear fuel, i.e. the remaining will be eventually similar to the naturally occurring uranium isotopes and their daughters.

Considering the potential that radionuclides released from repository migrate through geosphere and consequently come into contact with man, the extent of hazard due to

Table 4. Radioactivity of Activation and Fission Products Contained in PWR45

Time(yr)	Activation Products			Fission Products			
	C-14	Cl-36	Nb-94	Se-79	Kr-85	Sr-90	Y-90
1	1.33E+00	1.28E-02	6.04E-01	5.54E-04	1.14E+04	9.43E+04	9.43E+04
5	1.33E+00	1.28E-02	6.03E-01	5.54E-01	8.82E+03	8.57E+04	8.58E+04
10	1.33E+00	1.28E-02	6.03E-01	5.54E-01	6.38E+03	7.61E+04	7.61E+04
30	1.32E+00	1.28E-02	6.03E-01	5.54E-01	1.75E+03	4.73E+04	4.73E+04
40	1.32E+00	1.28E-02	6.03E-01	5.54E-01	9.18E+02	3.73E+04	3.73E+04
50	1.32E+00	1.28E-02	6.03E-01	5.54E-01	4.81E+02	2.94E+04	2.94E+04
60	1.32E+00	1.28E-02	6.02E-01	5.54E-01	2.52E+02	2.32E+04	2.32E+04
70	1.32E+00	1.28E-02	6.02E-01	5.54E-01	1.32E+02	1.83E+04	1.83E+04
100	1.31E+00	1.28E-02	6.02E-01	5.53E-01	1.90E+01	8.94E+04	8.94E+03
300	1.28E+00	1.28E-02	5.97E-01	5.52E-01	-	7.65E+01	7.65E+01
500	1.25E+00	1.28E-02	5.93E-01	5.51E-01	-	6.55E-01	6.55E-01
700	1.22E+00	1.28E-02	5.89E-01	5.50E-01	-	5.61E-03	5.61E-03
1000	1.18E+00	1.28E-02	5.83E-01	5.48E-01	-	-	-
Time(yr)	Activation Products			Fission Products			
	C-14	Cl-36	Nb-94	Se-79	Kr-85	Sr-90	Y-90
1	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.36E+05
5	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.24E+05
10	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.11E+05
30	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	6.98E+04
40	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	5.54E+04
50	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	4.40E+04
60	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	3.49E+04
70	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	2.77E+04
100	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.39E+04
300	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.36E+02
500	1.72E+01	1.56E-01	1.06E+00	1.49E-01	4.26E-02	5.95E-01	1.34E+00
700	1.72E+01	1.56E-01	1.06E+00	1.48E-01	4.26E-02	5.95E-01	1.32E-02
1000	1.72E+01	1.56E-01	1.06E+00	1.48E-01	4.26E-02	5.95E-01	

1. C-14 from activation products of fuel structural materials and nuclear fuel materials
2. Cl-36 from activation products of nuclear fuel materials
3. Nb-94 from activation products of fuel structural materials

radionuclides can be recognized in term of "radiotoxicity" or "hazard index". Because of the features of radionuclide maigration pathway to the body, in this study, radiotoxicity of nuclide is considered as the term of ingestion hazard index defined as the radioactivity divided by the radioactivity concentration limit for drinkable water for general public. Here, the radiotoxicity of radioactive waste disposed of is closed to the potential hazard rather than any actual risks associated with the analytical safety issues of the repository system.

To estimate how long and what extent the potential hazard of radionuclides in spent fuel disposed of in underground repository would remain in the environment, therefore, it is very meaningful to compare the total hazard indices of radionuclides in spent fuel with that of

Table 5. Radioactivity of Actinides and Daugthers Contained in PWR45, Ci/MtHM

Time(yr)	Pb-210	Po-210	Ra-223	Ra-226	Th-229	Th-230	Th-234	Pa-233	U-234
1	8.47E-09	7.25E-09	1.79E-06	5.98E-08	3.59E-07	4.96E-05	3.12E-01	5.72E-01	1.21E+00
5	2.11E-08	2.11E-08	4.96E-06	1.84E-07	3.69E-07	9.45E-05	3.12E-01	5.73E-01	1.28E+00
10	6.27E-08	6.27E-08	8.64E-06	4.52E-07	3.87E-07	1.54E-04	3.12E-01	5.76E-01	1.35E+00
30	7.79E-07	7.79E-07	2.09E-05	2.90E-06	5.17E-07	4.23E-04	3.12E-01	5.98E-01	1.63E+00
40	1.63E-06	1.63E-06	2.60E-05	5.05E-06	6.19E-07	5.76E-04	3.12E-01	6.12E-01	1.76E+00
50	2.92E-06	2.92E-06	3.07E-05	7.86E-06	7.46E-07	7.39E-04	3.12E-01	6.26E-01	1.87E+00
60	4.72E-06	4.72E-06	3.50E-05	1.14E-05	8.98E-07	9.12E-04	3.12E-01	6.42E-01	1.98E+00
70	7.08E-06	7.09E-06	3.92E-05	1.57E-05	1.08E-06	1.09E-03	3.12E-01	9.57E-01	20.7E+00
100	1.81E-05	1.81E-05	5.07E-05	3.34E-05	1.78E-06	1.69E-03	3.12E-01	7.04E-01	2.32E+00
300	2.96E-04	2.96E-04	1.21E-04	3.73E-04	1.38E-05	6.71E-03	3.12E-01	9.69E-01	3.07E+00
500	9.90E-04	9.90E-04	1.91E-04	1.14E-03	4.14E-05	1.24E-02	3.12E-01	1.16E+00	3.22E+00
700	2.31E-03	2.31E-03	2.72E-04	2.32E-03	9.07E-05	1.82E-02	3.12E-01	1.34E+00	3.26E+00
1000	4.79E-03	4.79E-03	3.78E-04	4.80E-03	2.02E-04	2.70E-02	3.12E-01	1.48E+00	3.26E+00
Time(yr)	U-236	Np-237	Np-239	Pu-238	Pu-239	Pu-240	Pu-242	Am-241	Am-243
1	3.35E-01	5.72E-01	3.40E+01	5.62E+03	4.15E+02	6.58E+02	2.43E+00	4.37E+02	3.40E+01
5	3.35E-01	5.73E-01	3.40E+01	5.52E+03	4.15E+02	6.60E+02	2.43E+00	1.31E+03	3.40E+01
10	3.35E-01	5.76E-01	3.40E+01	5.30E+03	4.15E+02	6.62E+02	2.43E+00	2.18E+03	3.40E+01
30	3.35E-01	5.98E-01	3.39E+01	4.53E+03	4.15E+02	6.67E+02	2.43E+00	4.07E+03	3.39E+01
40	3.35E-01	6.12E-01	3.39E+01	4.19E+03	4.15E+02	6.68E+02	2.43E+00	4.48E+03	3.39E+01
50	3.36E-01	6.26E-01	3.39E+01	3.87E+03	4.15E+02	6.68E+02	2.43E+00	4.69E+03	3.39E+01
60	3.36E-01	6.42E-01	3.38E+01	3.58E+03	4.15E+02	6.68E+02	2.43E+00	4.80E+03	3.38E+01
70	3.36E-01	6.57E-01	3.38E+01	3.31E+03	4.15E+02	6.68E+02	2.43E+00	4.83E+03	3.38E+01
100	3.37E-01	7.04E-01	3.37E+01	2.61E+03	4.14E+02	6.67E+02	2.43E+00	4.74E+03	3.37E+01
300	3.41E-01	9.69E-01	3.31E+01	5.44E+02	4.12E+02	6.53E+02	2.43E+00	3.47E+03	3.31E+01
500	3.44E-01	1.16E+00	3.25E+01	1.15E+02	4.10E+02	6.40E+02	2.43E+00	2.52E+03	3.25E+01
700	3.48E-01	1.34E+00	3.19E+01	2.46E+01	4.08E+02	6.26E+02	2.43E+00	1.83E+03	3.19E+01
1000	3.54E-01	1.48E+00	3.10E+01	2.63E+00	4.05E+02	6.07E+02	2.43E+00	1.13E+03	3.10E+01

uranium ore rather than the comparison of their radioactivities. Considering that the spent fuel is solidly disposed of in rock matrix, it would be reasonable that hazard index of spent fuel in the rock is compared with the hazard potential from a natural uranium deposited in the rock. When the hazard indices of various radionuclides are compared with that of natural uranium, it is also possible to select the important radiotoxic elements from the long-term safety point of view.

In order to evaluate which radionuclides in spent fuel pose greater hazard potential during the different phases of long-term period of disposal, the ingestion hazard indices of fission product elements and actinides of interest were compared with that of natural uranium ore, as shown in Fig.5 and 6, respectively. Here, ingestion hazard index of one ton of natural uranium including all daughters was estimated to be $1.7 \times 107 m^3$ of water/tHM. In general, the radionuclides can be separated into two categories. One contains fission products such as Sr-90 and Cs-137 with extremely high hazard indices in a deep repository but it comes down rapidly during a couple of hundred years as radionuclides decay. Another includes most

Table 6. Photon Spectrum of PWR45 and CANDU

Mean Energy	Cooling Time of PWR45 (Years)				Cooling Time of Spent CANDU Fuel			
(MeV)	30yr	50yr	70yr	100yr	30	50	70	100
0.001	1.550E+15	9.821E+14	6.326E+14	3.387E+14	2.577E+14	1.626E+14	1.038E+14	5.454E+13
0.025	3.056E+14	1.909E+14	1.204E+14	6.132E+13	5.203E+13	3.188E+13	1.981E+13	9.725E+12
0.038	3.679E+14	2.239E+14	1.391E+14	6.891E+13	6.240E+13	3.840E+13	2.392E+13	E1.182+13
0.058	3.356E+14	2.365E+14	1.731E+14	1.175E+14	5.501E+13	3.802E+13	2.717E+13	1.774E+13
0.085	1.668E+14	1.026E+14	6.405E+13	3.194E+13	2.810E+13	1.732E+13	1.075E+13	5.275E+12
0.125	1.270E+14	6.895E+13	4.186E+13	2.054E+13	1.978E+13	1.144E+13	6.945E+12	3.376E+12
0.225	1.406E+14	8.558E+13	5.296E+13	2.610E+13	2.352E+13	1.443E+13	8.932E+12	4.371E+12
0.375	5.847E+13	3.596E+13	2.231E+13	1.096E+13	8.896E+12	6.105E+12	3.789E+12	1.858E+12
0.575	2.552E+15	1.605E+15	1.010E+15	5.049E+14	4.462E+14	2.808E+14	1.768E+14	8.838E+13
0.85	3.384E+13	1.061E+13	4.578E+12	1.880E+12	3.787E+12	1.414E+12	6.948E+11	3.057E+11
1.25	3.634E+13	7.722E+12	2.275E+12	6.706E+11	3.487E+12	8.431E+11	2.971E+11	1.062E+11
1.75	1.039E+12	3.070E+11	1.232E+11	4.750E+10	1.128E+11	3.947E+10	1.841E+10	7.858E+09
2.25	1.151E+08	4.461E+07	2.318E+07	1.052E+07	7.746E+06	3.306E+06	2.029E+06	1.147E+06
2.75	6.939E+08	5.628E+08	4.595E+08	3.417E+08	1.753E+06	1.455E+06	1.219E+06	9.472E+05
3.5	2.770E+07	1.344E+07	6.796E+06	2.840E+06	2.007E+05	1.713E+05	1.573E+05	1.485E+05
5	1.184E+07	5.742E+06	2.901E+06	1.209E+06	8.526E+04	7.261E+04	6.659E+04	6.283E+04
7	1.365E+06	6.613E+05	3.336E+05	1.386E+05	9.724E+03	8.256E+03	7.561E+03	7.129E+03
9.5	1.568E+05	7.592E+04	3.828E+04	1.587E+04	1.112E+03	9.427E+02	8.627E+02	8.132E+02

• Summation of photon spectrum for the activation products of fuel and structural materials, the actinides and the fission products.

Table 7. Neutron Source of PWR45

Neutron	PWR45							
	30years		50years		70years		100years	
Spirce	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous
U-238	-	1.177E+04	-	1.177E+04	-	1.117E+04	-	1.177E+04
Pu-238	4.311E+06	7.31E+05	3.684E+06	6.007E+05	3.147E+06	5.133E+05	2.486E+06	4.054E+05
Pu-239	3.023E+05	-	3.022E+05	-	3.020E+05	-	3.018E+05	-
Pu-240	5.053E+05	2.664E+06	5.064E+05	2.669E+06	5.063E+05	2.669E+06	5.053E+05	2.663E+06
Pu-242	-	1.073E+06	-	1.073E+06	-	1.073E+06	-	1.073E+06
Am-241	3.906E+06	-	4.503E+06	-	4.635E+06	-	4.546E+06	-
Am243	2.893E+04	-	2.888E+04	-	2.882E+04	-	2.874E+04	-
Cm-242	2.432E+04	1.180E+05	2.220E+04	1.077E+05	2.027E+04	9.833E+04	1.767E+04	8.576E+04
Cm-243	2.638E+04	-	1.616E+04	-	9.935E+03	-	4.790E+03	-
Cm-244	2.157E+06	2.596E+08	1.003E+06	1.208E+08	4.665E+05	5.617E+07	1.480E+05	1.782E+07
Cm-246	-	4.331E+06	-	4.319E+06	-	4.306E+06	-	4.287E+06
Cm-248	-	2.021E+04	-	2.021E+04	-	2.021E+04	-	2.021E+04
Total	1.126E+07	2.686E+08	1.007E+07	1.296E+08	9.121E+06	6.486E+07	8.043E+06	2.637E+07

Table 8. Neutron Source of CANDU

Dacay Time	30years		50years		70years		100years	
Source	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous	(Alpha, n)	Spontaneous
U-238	-	1.250E+04	-	1.250E+04	-	1.250E+04	-	1.250E+04
Pu-238	4.667E+04	7.611E+03	3.986E+04	6.500E+03	3.404E+04	5.551E+03	2.687E+04	4.382E+03
Pu-239	1.266E+05	-	1.265E+05	-	1.264E+05	-	1.263E+05	-
Pu-240	1.802E+05	9.501E+05	1.799E+05	9.482E+05	1.795E+05	9.462E+05	1.789E+05	9.432E+05
Pu-242	-	8.902E+04	-	8.902E+04	-	8.902E+04	-	8.902E+04
Am-241	5.233E+05	-	6.065E+05	-	6.255E+05	-	6.139E+05	-
Am242	9.568E+01	4.643E+02	8.734E+01	4.238E+02	7.973E+01	3.869E+02	6.953E+01	3.374E+02
Cm-244	4.472E+03	5.384E+05	2.080E+03	2.504E+05	9.673E+02	1.165E+05	3.068E+02	3.694E+04
Cm-246	-	1.859E+03	-	1.854E+03	-	1.848E+03	-	1.840E+03
Total	8.823E+05	1.600E+06	9.558E+05	1.309E+06	9.673E+05	1.172E+06	9.472E+05	1.088E+06

actinides and their daughters and iodine-129, of which radioactivity is relatively low but their hazard indices still remain in spent fuel for quite a long time. Especially, plutonium isotopes such as Pu-239 and Pu-240 are found to be long-term hazardous element over 10,000 years, and Ra-226 and Pb-210 are remarkable after 100,000 years although their hazard indices are relatively lower than that of natural uranium. Such radionuclides contents in PWR45 are given in Table 4 to 5. This information will be used as the source inventory in identifying and analyzing all the processes that may cause the radionuclide migration to biosphere and also demonstrating how repository barriers would perform and how radionuclides escaped from the repository behavior in the natural environment.

5.3. Radiation Intensity

Radiation shielding is an inevitable matter in designing repository system and radiation protection analyses during the repository operation period. Radiation sources from spent fuel are the gamma radiation due to most fission products' radioactive decay and the neutron due to actinides' spontaneous fission and (α, n) reaction.

As mentioned previously, radioactivity in spent fuel is due to the fission products and actinides in spent fuel material and activation products of fuel structural material. Therefore, radiation source strength is also separated with the same manner. Table 6 includes gamma radiation intensities of PWR45 and CANDU7.5 expressed as numbers of photons emitted for a second with respect to the specific average energy group. In Table 7 to 8, neutron sources due to (α, n) and spontaneous fission reaction are included. In the case of spent PWR fuel, neutron source is dominated by spontaneous fission due to Cm-244 and for spent CANDU fuel by Pu-240.

6. Conclusions

As a reference disposal capacity of the reference geological repository system to be developed, spent fuel inventories were estimated to be approximately 36,000tHM based on the Nuclear Energy Plan of the Long-term National Power Development Plan, 24 PWR and 4 CANDU reactors. Of these

projected spent fuel inventories, PWR fuels comprise ~20,000tHM (55%) and CANDU fuels ~16,000tHM (45%).

The reference spent PWR and CANDU fuels whose bounding characteristics could be representative of all spent fuels generated during the lifetime of nuclear power plants of interest were defined in terms of initial enrichment, burnup, dimension, gross weight, etc. The reference PWR spent fuel selected has the average burnup of 45,000MWd/tHM (initial enrichment of 4.0wt%) and is cooled for 40 years after irradiation before the encapsulation and disposal. An alternative burnup level is 55,000MWd/tHM. Its weight and dimensions are 665kg and 21.42 cm^2 (cross-section)×453 cm (length), respectively. For the CANDU fuel, the reference fuel burnup is 7,500MWd/tHM and the fuel dimensions are 10cm(diameter) × 49.5cm (length).

Isotopic composition, radiological properties including radioactivity, thermal energy, hazard index, and radiation intensity of the reference PWR and CANDU fuels were quantitatively identified to provide basic information for the concept developing works and the performance/safety assessment of a repository system.

The reference spent fuels and their bounding characteristics proposed in this study could be applied in fuel material balance evaluation for the various types of back-end fuel cycle studies. Considering the feature that a HLW disposal technology development program would be lasted for several decade years, however, such bounding reference fuel characterization values should be revised further with respect to the trend of the extended burnup level of spent fuel and long-term strategy of nuclear energy. In addition, a spent fuel characteristics data base program just like the US' s CDB program has to be systematically carried out in order to evaluate the effects of the evolving characteristics of the spent fuel on its long-term behavior in the repository and to collect information for a national long-term spent fuel management strategy.

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